Opto/Mechanical Design of the Micro-Arcsecond Metrology Testbed Interferometer

Andrew Carlson, Stuart Shaklan, Randall Bartos, Steve Azevedo

Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Dr., Pasadena, CA 91109

ABSTRACT

The Micro Arcsecond Metrology Testbed (MAM) is a laboratory-based, long baseline, white-light interferometer inside a vibration-isolated vacuum tank. The single baseline, high precision interferometer will be able to observe a translating, artificial star at a distance of 10.74 meters with 5 μas accuracy. The MAM testbed consists of an artificial star, laser metrology and a high precision interferometer. This paper addresses the design and characteristics of the interferometer. The interferometer functions include both angle- and optical-path tracking. The optics are arranged to form dispersed fringes in a channeled spectrum on a charge coupled device (CCD) and a true white-light fringe on an avalanche photodiode (APD), while at the same time producing guide spots for angle tracking.

Keywords: Interferometer, optical delay, metrology, precision optics, angle tracking

1. INTRODUCTION

The Space Interferometry Mission (SIM), proposed by NASA has very high precision measurement requirements for both the spacecraft geometry and white light fringe detection. The purpose of the MAM testbed is to develop the techniques and to solidify the error budgets required for a successful mission. Shaklan et al give an overview of the MAM testbed in a companion paper[1].

The MAM testbed interferometer has been designed to represent a $1/5^{th}$-scale representation of a single baseline of the SIM instrument. There are five primary sections to the interferometer: the star light collection system; the optical path delay line; fringe and guide light separators; the beam combiner; and the internal metrology retro-reflectors.

The star light collection system is comprised of the siderostat mirrors, fast steering mirrors and the delay line input mirrors. The delay line is a back-to-back cat's eye retro-reflector that incorporates a novel dual-parabolic optic. The beam combiner includes a sandwich type beam splitter, a fringe dispersion/guide mirror assembly, two off-axis parabolas, a CCD camera and an APD-fiber/metrology retro-reflector assembly. The internal metrology retro-reflectors are the hollow corner cubes mounted in the siderostats, and the cat's eye formed by one of the parabolas with the front surface of the APD fiber/metrology retro-reflector assembly.

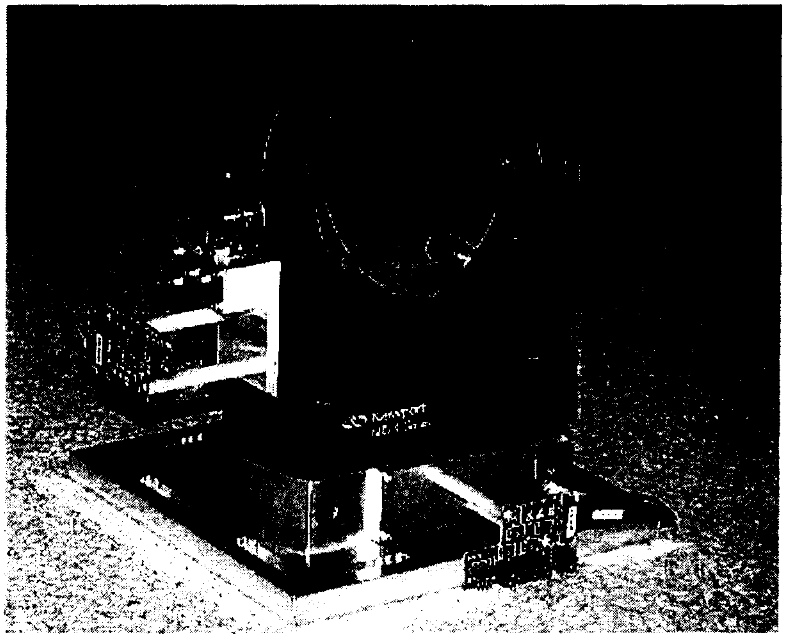
2. INTERFEROMETER REQUIREMENTS

The picometer laser metrology and the white-light fringe detection systems dictate that the instrument be placed in a vibration isolated vacuum chamber. The vacuum chamber configuration is a cylinder 12.19 meters long and 2.44 meters in diameter. The envelope inside the vacuum chamber determined that the baseline separation, the distance between the centers of the two-siderostat mirrors, be 1.83 meters and that the star be placed 10.74 meters from the siderostats. The environment inside the chamber provides thermal and vibration constraints. The opto-mechanical design should be thermally stable to < 10mK/24hr, and will see a vibration spectrum < 1μm above 1Hz, <100 nm above 10Hz.

2.1 Star Light Collection System

The star light collection system incorporates two siderostat mirrors, each with a hollow corner cube retro-reflector for metrology, two fast steering mirrors and three delay line input mirrors. The siderostat mirrors are the first optical components in the interferometer. They collimate the light from the artificial star (see sect. 3.3.1). They are the entrance apertures and the distance between their centers establishes the baseline separation. Each siderostat mirror is mounted in a three-axis cell that is placed into a commercial two-axis gimbal mount. The cell is attached to the mirror by three edge-bonded flexures. The three-axis mirror cell allows for the adjustment of the siderostat surface and its center in azimuth, elevation and piston defined by the vertex corner of the metrology corner cube, to within 1.0 μm of the two axes of the gimbal mount. The gimbal mounts are part # 605-4 from the Newport Corporation, Irvine CA. They are equipped with 0.1 μm resolution DC motors and 0.04 μrad resolution rotary encoders for diagnostic information (see figure 1). The motors are DC Encoder Mikes from the Oriel Corporation, Stratford CT. The encoders are 5T16 Series rotary encoders from MicroE, Incorporated, Natick MA. The 0.1 μm resolution DC motor translates into 1.6 μrad pointing resolution of the siderostat.

<u>Figure 1</u> Modified Newport gimbal mount.



The fast steering mirror is bonded into an Invar flexure that is attached to a commercial PZT tip/tilt translators with ± 625 μrad range with resolution ~100 nrad. The PZT devices are from Polytec PI, part # S-316.10. The fast steering mirrors actively maintain the line-of-site from the siderostats to the delay line and compensate for any vibrations within the interferometer during an observation.

The delay line input mirrors are merely stationary fold mirrors that direct the light from the fast steering mirrors into the delay line. They are mounted in Newport Corporation part # U300-A tip/tilt mirror mounts. There is asymmetry between the two arms of the interferometer at this point. One side has a single fold mirror at 45 degrees. The other side has two mirrors at 22.5 degrees that form a hollow penta prism. This hollow penta prism provides a necessary flip to insure proper superposition of the image and polarization.

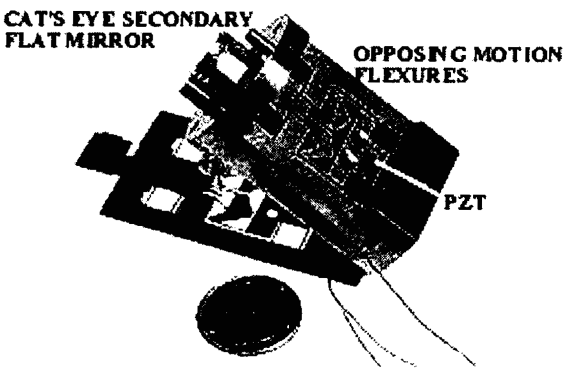
2.2 Optical Path Delay Line

The optical path delay line is made up of two cat's eye retro-reflectors. A cat's eye retro-reflector is formed from a parabola and a small flat mirror. Light from the delay line input mirrors feeds the parabola off-axis but normal to the vertex. The light is focused onto the small flat and reflected to an off-axis section of the parabola, opposite from the input section. What is novel about this delay line is that the two cat's eyes are in a back-to-back configuration in a common athermalized housing (see figure 2).

Figure 2 Optical path delay line.

There are several advantages to this approach. There is a 4x magnification of the delay motion. This means that the mechanical motion required to maintain the peak visibility of the white light fringe is ¼ that of the OPD introduced by a translation of the star. The two parabolas are ground and polished into a single substrate, eliminating the weight of one of the largest mirrors in the system. The need for a stable mount that would hold the two parabolas in position relative to each other is also eliminated.

Figure 3 Momentum compensated PZT actuator.



On either end of the athermalized delay line housing are the small secondary flat mirrors. Each mirror is bonded into flexures that are integral to a momentum compensated PZT actuator (see figure 3). One mirror is used for dithering the white light fringe and the other is used for fine delay line positioning. Each actuator has a range of 6 μm with sub-nanometer resolution.

2.3 Fringe and Guide Light Separators

Immediately following the delay line is the fringe and guide light separators. These are dual optic assemblies consisting of a window with a first surface dichroic coating co-mounted with precision tip/tilt mirror. The dichroic coating acts as a mirror for the fringe light (600 nm - 900 nm) and internal metrology (1319 nm) and passes shorter wavelength light for guiding (400 nm - 550 nm). The rear mirror reflects the guide light along the path of the fringe light but at a slightly different angle. This angle separates the guide light from the fringe light at the detector. Both optics are mounted in a modified commercial tip/tilt mount (Newport Corp. part # U300-A). Modifications to the tip/tilt mount allow the window to be held in the stationary section. PZT actuators will be installed for fine adjustment of the guide spot mirror once the system is under vacuum.

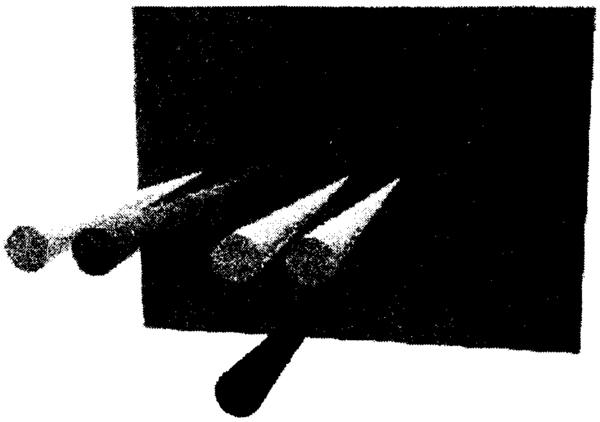
2.4 Beam Combiner

Light from the fringe/guide separators meets at the beam splitter of the beam combiner. This is the plane of interference. Following the beam splitter are two subsystems. Fifty percent of the light goes to the dispersed white light fringe and guide spot CCD. The other fifty percent of the light goes to the APD-fiber/internal metrology retro-reflector.

2.4.1 Dispersed White Light Fringe/Guide Spot CCD

The dispersed white-light fringe/guide spot CCD system includes the dispersion prism/guide mirror assembly, an off-axis parabola and the CCD. The dispersion prism/guide mirror assembly disperses the white light fringe and folds the guide light to follow the path of the fringe light. This is a dual optic device that uses the same modified tip/tilt mount of the fringe/guide separators. A single fused silica prism is mounted in the stationary section of the mount and a flat mirror is mounted in the tip/tilt section. The first surface of the prism has a dichroic coating that transmits the fringe light and reflects the guide light. The fringe light is initially dispersed after its first pass through the prism. The rear mirror reflects the light back for a second pass through the prism. The result is a nearly linear dispersion by wave number, (inverse wavelength). The guide light is reflected along the path of the now dispersed fringe light. Both fringe and guide light are focused onto the CCD by the off-axis parabola. The 600nm – 900nm fringe is dispersed along a single row of 190 pixels while at the same time the 400nm - 550nm guide light forms two focused spots (one from each arm), each positioned above and below the dispersed light, at the corners of four adjacent pixels acting as quad cells (see figure 4).

Figure 4 Dispersed fringe and guide spots on CCD.



2.4.2 APD Fiber/Internal Metrology Retro-reflector

The APD fiber/internal metrology retro-reflector system includes an off-axis parabola and an APD-fiber/retro-reflector assembly. The APD-fiber/retro-reflector assembly is a 700 μm thick, short wave pass filter optically contacted to a mirror substrate with a 1.0mm thru-hole. A 100 micron core multi-mode fiber mounted in a 1 mm diameter tube is placed in the hole so that it contacts the back of the filter and is bonded in place. The off-axis parabola focuses light from the beam splitter onto the short wave pass filter and retro-reflects the internal metrology. The starlight passes through the filter to the fiber and APD. This is ideal for the internal metrology beam but leads to a slight defocus (< 10 microns) of the starlight beam. The fiber collects all of the starlight despite the small amount of defocus.

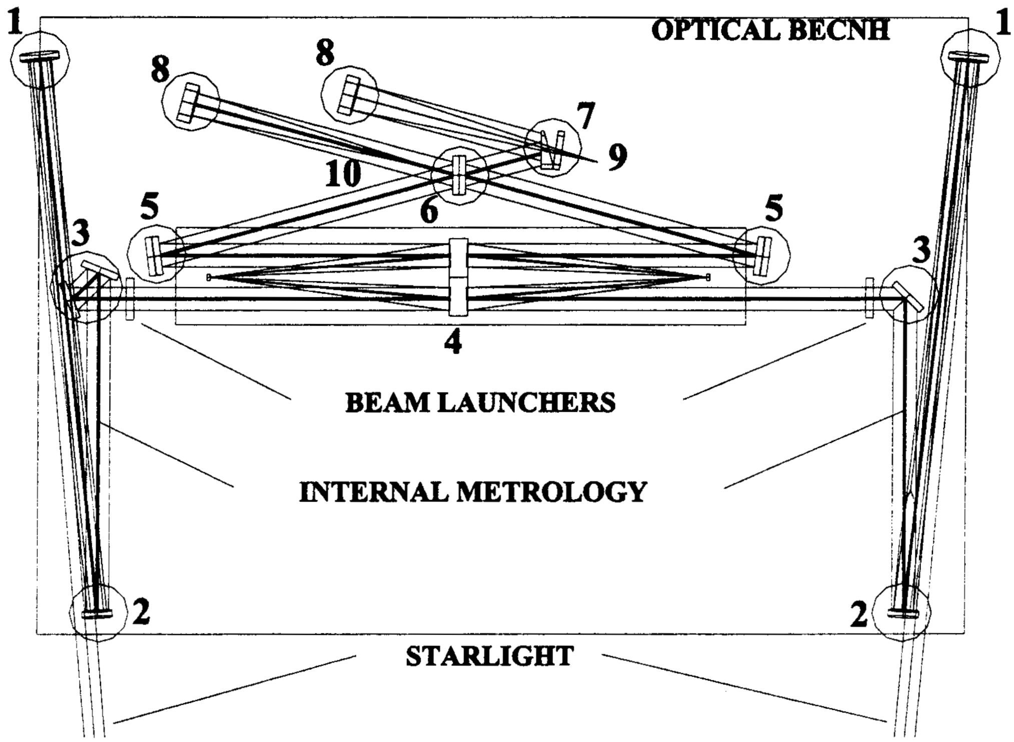
2.5 Internal Metrology

The internal metrology measures the length between the siderostat corner cube and the APD-fiber/internal metrology retro-reflector for each arm of the interferometer[2]. The hollow corner cube retro-reflector in the siderostat mirror is a constructed from three prisms. The main body of the corner cube is made of ULE while other two pieces are made or Zerodur. Both materials exhibit a comparable CTE but Zerodur is easier to work with in the fabrication stage. The main body is ULE to insure a CTE match with the siderostat.

The off-axis-focusing parabola and the APD-fiber/internal metrology retro-reflector make up a cats eye retro-reflector. This retro-reflector is the common fiducial for both arms of the internal metrology.

3. OPTICAL DESIGN

Figure 5 MAM interferometer layout.



1. Siderostat
2. Fast Steering Mirror
3. Delay Line Input Mirror
4. Delay Line w/ Dual Parabola and Cats Eye Secondary Flat Mirror
5. Fringe and Guide Light Separators
6. Beam Splitter
7. Dispersion Prism/Guide Mirror Assembly
8. Off-Axis Focusing Parabola
9. CCD
10. APD-Fiber/Internal Metrology Retro-Reflector

3.1 Design Constraints

The primary constraints, which have been driving the interferometer optical design, are:

- A 1.8 meter baseline. The baseline separation along with the standoff distance of the artificial star provides an astrometric measurement with 5μas accuracy.
- Curved siderostat mirrors to compensate for a point source at a finite distance.
- Entrance aperture size of 45.72mm. Sufficient light and this aperture size allow for the use of commercial optics and mounts.
- The interferometer optics need to perform three different functions.

  A. White light fringe detection over the 600 nm to 900 nm wavelength range.
  B. Course acquisition and guiding over the 400 nm to 550 nm wavelength range.
  C. Internal metrology at 1319 nm.

- Optics require thermal stability within 10mK/24hr.
- Minimize the number optical components to cut losses at optical interfaces.
- Design layout to accommodate two interferometers on the same bench, looking at the same star.
- Accommodate either siderostats or beam compressors. Beam compressors would be representative of the new SIM configuration.
- Utilize commercially available components wherever possible.
- Minimize the number of special optics and mounts.

3.2 Material Selection

The selection of materials was based on the lowest CTE materials available. All reflective components are fabricated in Corning ULE or Schott ZERODUR materials and all transmissive optics are fabricated in fused silica.

- The Coefficient of Thermal Expansion (10^{-6}/K) of the materials is:
  - Zerodur - <0.5 (20-30°C)
  - ULE – 0.03 (5-35°C)
  - Fused Silica - 0.51

Note: All mirrors are coated with protected silver unless otherwise specified.

3.3 Star Light Collection System design

3.3.1 The Siderostat Mirror

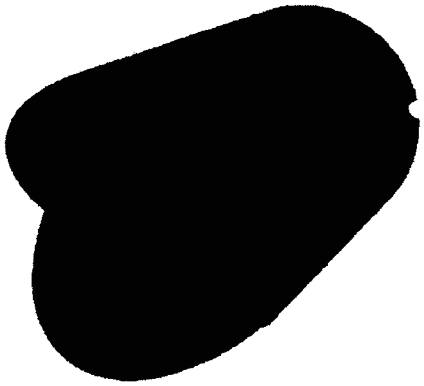
The first optical components to receive starlight are the siderostat mirrors (see figure 5). Considering that the artificial star is a point source only 10.74 meters away, flat siderostat mirrors would provide a defocused spot on the detectors. The correction is to apply a spherical surface to the siderostat with a vertex radius equal to twice the source distance, (~21.5m radius). This results in a collimated input for the rest of the interferometer. Because the internal metrology sees all mirrors in the interferometer except for the siderostat (instead it retro-reflects from a corner cube mounted in the siderostat), the siderostat is the only element that could be modified to compensate for starlight focus without affecting the internal metrology.

The focal length of the sphere divided by the diameter of the entrance aperture produces a large f-number, ≈ 235. Such a slow sphere allowed for a ± 215mm tolerance in the vertex radius during fabrication. The tough specification for the optician is a ± 10mm radius difference between the two mirrors. The radius difference specification will maintain at least a $\lambda/20$ error contribution when the two arms interfere. The surface figure is specified at $\lambda/20$ p-v. This specification was the best any vendor felt they could achieve.

There is a ∅12.7mm through hole centered on the mirror at an angle of 4.40°. Internal and external metrology reference a hollow corner cube mounted in the hole. The 4.40° angle insures both internal and external metrology beams are included in the FOV of the corner cube. The mirror substrate and the main body of the corner cube are both ULE. The CTE match of the two parts makes it an athermalized design.

The body of the corner cube is cylindrical when assembled (see figure 4), and is bonded into the hole in the siderostat. By bonding the two smaller pieces to the face of the main body and not to each other, the vertex position never moves. Thermal expansion results only in piston in the plane of the facet face.

Figure 4 Cylindrical retro-reflector.



3.3.2 The Fast Steering mirror

The fast steering mirror is a simple flat. The size of this mirror is kept to a minimum because it is an actuated component. The surface figure is specified at $\lambda/40$ p-v and the surface quality is 10-5 laser quality. The precision surface specifications are necessary to minimize the errors contributed by small amounts of beam walk over the surface.

3.3.3 The Delay Line Input Mirror

The delay line input mirrors are standard commercial off-the-shelf (COTS) Zerodur mirrors. These are stationary mirrors that fold the light from the fast steering mirror into the delay line. These mirrors are specified at $\lambda/20$ p-v surface figure and 15-5 laser quality surface.

3.4 The Delay Line

3.4.1 The Dual Parabolic Mirror

The dual parabolic mirror is a single Zerodur substrate with a concave parabola on each side. Registration of the two cat's eye retro-reflectors is intrinsic to the monolithic design of this mirror. There were several challenging targets to meet before delivery.

The substrate started out as a ∅17.78cm, two-sided optical flat parallel to 2 arcseconds. A 15.24cm parabola with a 474.375 mm focal length was ground and polished into each sided. During the optical figuring process, the parallel flat ring around the OD of the parabolas was used as an integral reference surface. The reference ring provided a means to monitor the angle between the optical axes of the two parabolas. The test setup was able to determine tilt to 1 arcsecond. The relative tilt specification was ≤ 30 arcseconds. The ∅15.24cm clear aperture was specified at $\lambda/20$ p-v surface figure and 40-20 surface quality.

3.4.2 The Cat's Eye Secondary Flat Mirror.

The cat's eye secondary flat mirror is the most highly polished mirror in the interferometer. The mirror is located at the focus of the parabola and is the surface that is dithered to track the center of the white-light fringe. Placed at the focal point for both the starlight and the internal metrology, surface errors will have the greatest effect on overall and differential optical path differences. The 5-2 laser quality surface is the most critical specification for this part. The surface figure is $\lambda/40$ p-v. The mirror is made of BK7. The material was is used to athermalize the delay line and is an exception to the materials chosen for reflective optics. The entire delay line is opto-mechanically athermalized to 2×10^{-6} °C^{-1}. The mirror is mounted in a momentum compensated, PZT actuated, titanium flexure. BK7 is a good CTE match for titanium.

3.5 Fringe and Guide Light Separators

The first element in the fringe and guide light separator is the fringe light dichroic mirror. The substrate is a fused silica window. The surface figure for both sides is specified at $\lambda/20$ p-v, the surface quality is 10-5 laser quality and the wedge is < 10 arcseconds.

The first surface has a dichroic coating that reflects 600 nm to 900 nm for the white-light fringe and 1319 nm for the internal metrology and transmits the 400 nm to 550 nm guide light. The second surface is AR coated for 400 nm to 550 nm.

There is a 500 μm difference in the thickness between the windows in each arm of the interferometer. The reason for this to avoid a superimposed ghost fringe due to second surface reflections.

The guide light mirror is the same mirror used in section 3.3.3, The delay line input mirror.

3.6 The Beam Combiner

3.6.1 The Beam Splitter

Two fused silica windows cemented together with a dielectric coating sandwiched in the middle make up the beam splitter. The windows are the same as the fringe light dichroic mirror. In the beam splitter the windows are of equal thickness to insure that the starlight from each arm sees the same optical path in glass before interference. The two outer surfaces of the beam splitter are AR coated for 400 nm to 1319 nm.

3.6.2 Dispersed White Light Fringe/Guide Spot CCD

3.6.2.1 The dispersion prism/guide mirror

The dispersion prism/guide mirror is a single prism of fused silica. The surface specifications are the same as the windows of section 3.5. The wedge angle is 15°28'20". The tolerance on the angle is fairly loose, about 0.5°. There is a "D-Cut" 25.4mm from the center, along the top of the prism to eliminate vignetting of the fringe and guide light along their path to the CCD. There is a small wedge ground along the length of the thick side of the prism that allows for the minimal clearance between the prism and the second-pass mirror. Reflecting the dispersed light immediately after its first pass through the prism provides the maximum overlap of the second-pass linearly dispersed fringe and the reflected guide light. The maximum overlap allows for the smallest clear aperture required by the focusing parabola.

The first surface of the prism has a dichroic coating that provides the opposite function of the dichroic coating on the fringe light dichroic mirror. The guide light, 400 nm to 550 nm, is reflected and the fringe light, 600 nm to 900 nm, is transmitted. The second surface is AR coated for 600 nm to 900 nm. The 1319 nm light from the internal metrology is not used on this side of the beam splitter.

3.6.2.2 The Second-Pass Mirror

The second-pass mirror is the same mirror used in section 3.3.3. This optics is "D-Cut" like the prism.

3.6.2.3 The Focusing Parabola Mirror

The focusing parabola mirror is a Ø76.2 mm off-axis section cut from a standard Ealing, on-axis parent parabola. The focal length is 500 mm and the off-axis distance is 45 mm. Three identical sections were cut from the parent. The surface figure is $\lambda/10$ with 60-40 surface quality. The off -axis distance allows placement of the CCD above and behind the fringe dispersion/guide mirror assembly. This location isolates the CCD as it is a major heat source inside the vacuum chamber.

3.6.2.4 The CCD Camera

The camera is a commercial CCD with very high signal to noise ratio. This device was purchased from DVC Camera Incorporated, San Diego CA. Separating the camera head from the power supply modified the camera. The separation allows the power supply, a major source of heat, to be located outside of the vacuum chamber.
The noteworthy specifications for the CCD are:

Part # - TC-245 CCD Sensor
Image format – 755(H) X 484(V)
Pixel size – 8.5μm (H) X 9.875μm
70 dB sensor. Full well >80,000 electrons; Noise equivalent signal <30 electrons, (typical 20 electrons)

The approximate size of the spot at focus is 9μm. There are 190 pixels for the dispersed white light fringe providing approximately 1.5 nm spectral resolution.

3.6.3 The APD-Fiber/Internal Metrology Retro-reflector

3.6.3.1 The Focusing Parabola Mirror

The parabola that focuses the starlight and internal metrology onto the APD fiber/internal metrology retro-reflector is one of the off-axis sections described above.

3.6.3.2 The Short Wave Pass Filter

The short wave pass filter is a stock etalon with a custom coating from CVI Laser Corporation, part # SWP-0-R1319-T600-900-ET/NO AR. The coating reflects >99% at 1319 nm and has an average transmission of 85 % between 600 nm to 90 nm.

4. SYSTEM THROUGHPUT

The artificial star is a single mode fiber with a 5 μm core. The coupling of the white light source to the fiber is poor. To insure that the size and surface treatments of the optics were appropriate, an initial interferometer throughput estimation was performed. Characteristics including the reflectivity and transmission were obtained from probable coating vendors and were applied to the appropriate surfaces. We determined that at all transmissive surfaces (e.g. fringe/guide separator and dispersing prism), dichroic coatings, as opposed to partially reflective coatings, were required to have sufficient throughput in the fringe, guide, and metrology beams. All reflective coatings are assumed to be protected silver. Table 1 shows the system throughput for the three beams. Column 1 lists the optical element that has the transmission (T) and reflection (R) characteristics of columns 2 and 3. The elements are listed in the order that they are encountered by the beams, e.g. the fringe light transmits through the dispersing prism twice but the guide light only reflects from the front surface once. The T and R are tabulated as appropriate to the relevant function and wavelength. Columns 4 and 5 show the fringe and guide light throughput. Column 6 shows the metrology beam throughput, accounting for the double reflection and transmission of the beam where appropriate.

TABLE 1.

R_{Ag}= 0.98

Element	R	T	Fringe Light 0.6-0.9 microns	Guide Light <0.6 microns	Int. Mtr. 1.3 microns
Siderostat	0.975		0.975	0.975	
Fast Steering Mirror	0.975		0.975	0.975	0.951
Fold Mirror 1	0.975		0.975	0.975	0.951
Fold Mirror 2	0.975		0.975	0.975	0.951
Delay Line Primary	0.975		0.975	0.975	0.951
Delay Line Secondary	0.975		0.975	0.975	0.951
Delay Line Primary	0.975		0.975	0.975	0.951
Fringe/Guide Sep 1	0.900	0.750	0.900	0.750	0.810
Fringe/Guide Sep 2	0.975			0.975	
Fringe/Guide Sep 1	0.900	0.750		0.750	
Beam Splitter	0.400	0.400	0.400	0.400	0.160
Dispersing Prism	0.900	0.890	0.890	0.900	
Dispersing Prism Refl	0.975		0.975		
Dispersing Prism	0.900	0.890	0.890		
Parabola	0.975		0.975	0.975	0.951
Int. Mtr. Refl.	0.950	0.950			0.950
Sidero. Corner Cube	0.927				0.927
Throughput			0.227	0.161	0.080

5. CONCLUSION

MAM is currently in the integration phase. Most of the optical component substrates have been delivered. The coatings will be applied as a batch to improve uniformity of the surfaces throughout the interferometer. The mounts for all of the optics have been received and are being tested for functionality. All of the optics and associated mounts and mechanisms will be precision cleaned before final assembly and insertion into the vacuum chamber. All of the surfaces have been tested interferometrically and the surface data is being applied to an optical model which is currently under development. The optical model is one component of a system modeling effort that will predict system performance targets and provide a diagnostic tool for the MAM testbed and eventually for SIM. Initial setup and testing of the interferometer will be performed with laser light and then fine-tuned to provide white light interference.

6. ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Don Moore designed the delay line. We have received many useful contributions from the entire MAM team.

7. REFERENCES

1. S. Shaklan, S. Azevedo, R. Bartos, A. Carlson, Y. Gursel, P. Halverson, A. Kuhnert, Y. Lin, R. Savedra, E. Schmidtlin, "The micro-arcsecond metrology testbed (MAM)," *Proceedings of SPIE Conf. On Astronomical Interferometry*, ed. R. Reasenberg, Vol. 3350, Kona, 1998.
2. Kuhnert, S. Shaklan, Y. Gursel, S. Azevedo, Y. Lin, "Metrology system for the micro-arcsecond metrology testbed," *Proceedings of SPIE Conf. on Astronomical Interferometry*, ed. R. Reasenberg , Vol. 3350, Kona, 1998.

To Doc rev Staff:

The letter from Lori Mooradian is ok for public release

Geoff Pomeroy

JPL

April 24, 1998

der place into the public domain
demonstrates possible designs for
ry Mission), more specifically beam
dware. This approval is necessary in
th the requirements of 22 CFR 125.4

tations and displays used at the
an Astronomical Society (AAS), and at
for Optical Engineering) conference
and the subsequent publication of
those proceeding

Your help in meeting necessary approval requirements for the release of this information would be greatly appreciated.

4/27/98

Approval, Richard Howard
Origins Program Executive

Sincerely,

Firouz M. Naderi
JPL Origins Program Manager
Space and Earth Science Directorate

cc: F. Elman, Documentation Review
G. Pomeroy, Legislative Affairs